# Experimental Investigation of Piston Heat Transfer in a Light Duty Engine Under Conventional Diesel, Homogeneous Charge Compression Ignition, and Reactivity Controlled Compression Ignition Combustion Regimes

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***Sandia National Laboratory***
***Advanced Engine Combustion Meeting***
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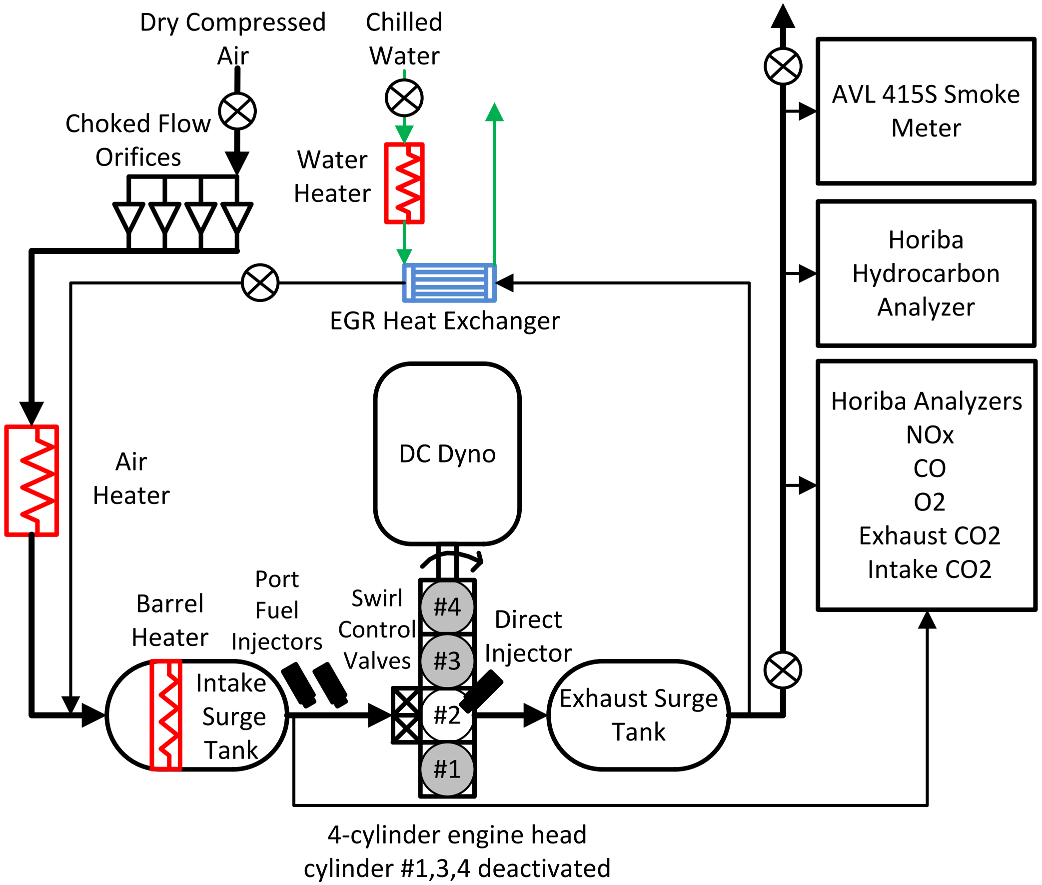
# Outline

- Experimental Setup
- Data Processing
- Results
- Summary / Conclusion

# Purpose

- To investigate heat flux in multiple LTC modes and compare to CDC
- The results presented seek to add understanding to an important difference between LTC and CDC which is heat transfer
- HCCI and RCCI are the LTC strategies investigated in this study

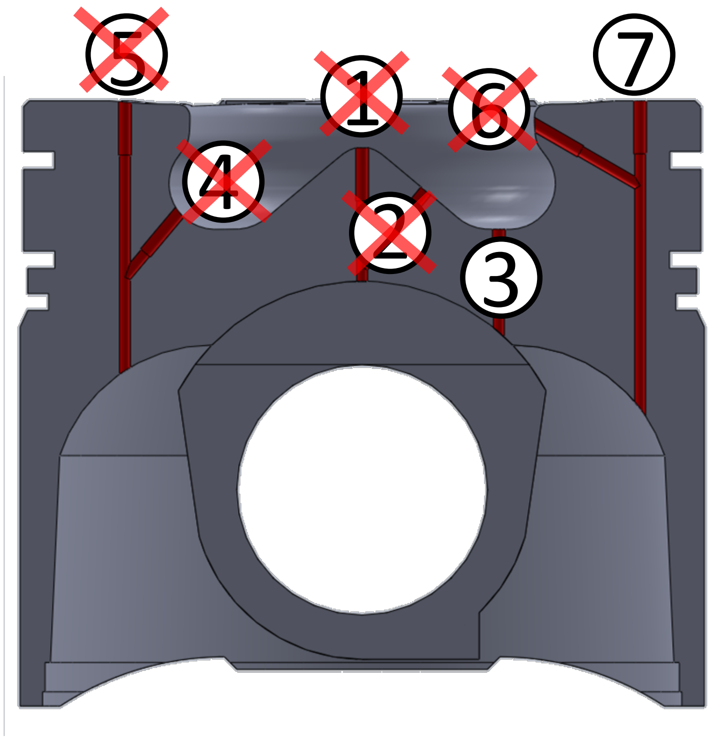
# Experimental Setup

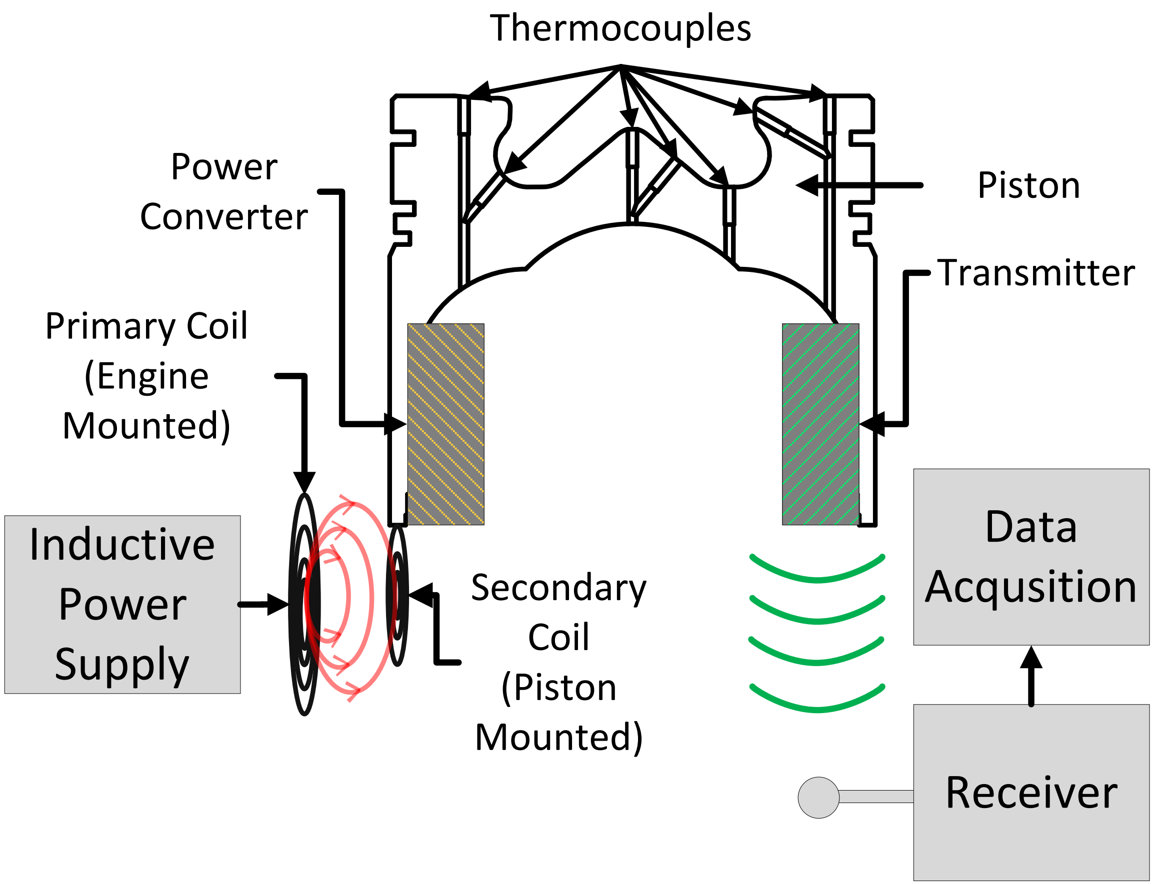



| | |
|---|---|
| **Engine Geometry** | |
| Base Engine | GM 1.9L Diesel |
| Compression Ratio | 16.3 |
| Displacement (Liters) | 0.477 |
| Stroke (mm) | 90.4 |
| Bore (mm) | 82 |
| Intake Valve Closing | -132° aTDC |
| Exhaust Valve Opening | 112° aTDC |
| Swirl Ratio | 1.5 -4.8 |
| Piston Bowl Type | Stock (Re-entrant) |
| **Port Fuel Injectors** | |
| Included Spray Angle | 20° |
| Injection Pressure (bar) | 2 to 10 |
| Rated Flow (cc/sec) | < 10 |
| **Bosch Common Rail Injector** | |
| Number of Holes | 7 |
| Hole Diameter (mm) | 0.14 |
| Included Spray Angle | 155° |
| Injection Pressure (bar) | 250 to 1000 bar |

# Experimental Setup

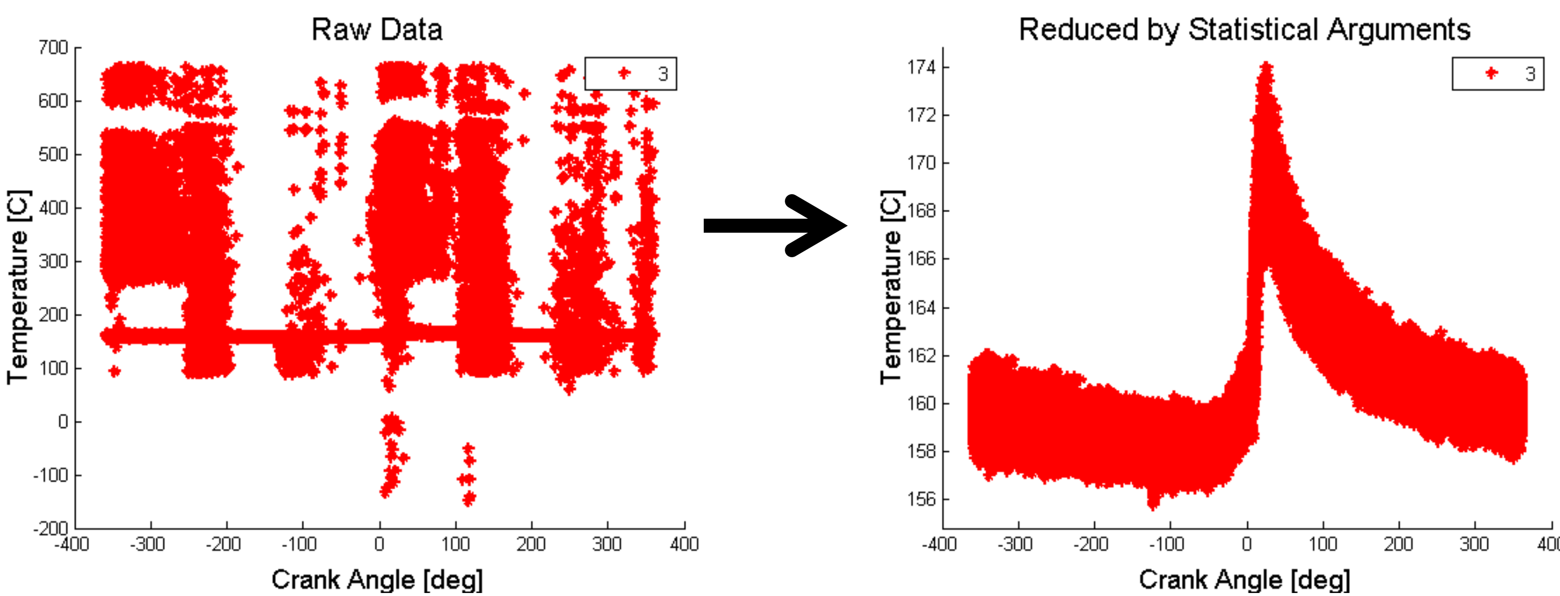




# Data Processing

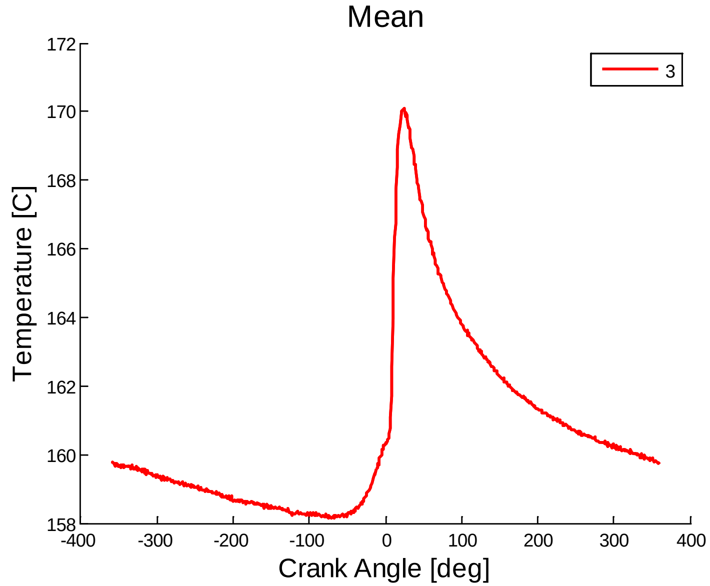
- At each crank-angle an outliers test is performed using the Generalized ESD Test for Outliers (Rosner 1983)
  - Statistical test
  - Assumes data has normal distribution
  - Allows for rejection of multiple outliers

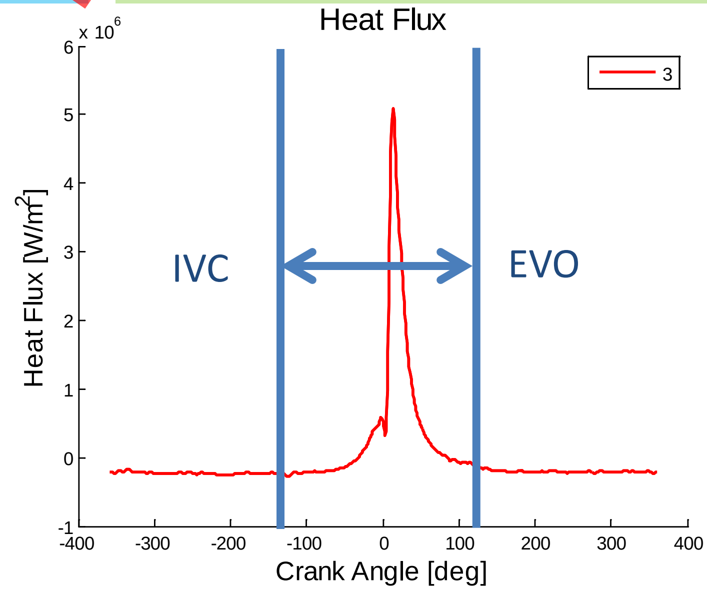


# Data Processing

- Mean temperature data are relatively clean
- Temperature data are filtered with 2000Hz low pass filter
- Fourier analysis is applied to find heat flux
- Integral of the dynamic heat flux over the full cycle is zero, but for the closed portion of the cycle it is meaningful

$$T(t) = T_m + \sum [A_n \cos(n\omega t) + B_n \sin(n\omega t)] \rightarrow \dot{q} = \overbrace{\cancel{\frac{k}{l}(T_m - T_l)}}^{\text{Steady}} + \overbrace{k \sum_{n=1}^{N} \sqrt{\frac{n\omega}{2\alpha}} [(A_n + B_n)\cos(n\omega t) - (A_n - B_n)\sin(n\omega t)]}^{\text{Dynamic}}$$



## Combustion Strategy Effect

### CDC / HCCI / RCCI

| | Mode 1 | Mode 2 | Mode 3 | Mode 4 |
|---|---|---|---|---|
| Speed (RPM) | 1490 | 1900 | 2300 | 2300 |
| IMEPg (bar) | 4.2 | 5.7 | 5.7 | 8 |
| CA50 (degATDC) | 4 | 5 | 4.5 | 8 |
| Swirl | 1.5 | 1.5 | 1.5 | 1.5 |
| Intake Temperature (C) | 75 | 50 | 50 | 35 |
| Intake Pressure (kPa) | 115 | 130 | 130 | 188 |
| ERG (%) | 0 | 0 | 0 | 55 |

## Swirl Effect

| | Mode 2 |
|---|---|
| Speed (RPM) | 1900 |
| IMEPg (bar) | 5.7 |
| CA50 (degATDC) | 5 |
| Swirl | 1.5, 2.5, 3.5, 4.8 |
| Intake Temperature (C) | 50 |
| Intake Pressure (kPa) | 130 |
| EGR (%) | 0 |

## Combustion Phasing Effect

| | Mode 2 |
|---|---|
| Speed (RPM) | 1900 |
| IMEPg (bar) | 5.7 |
| CA50 (degATDC) | 3, 5, 7, 9 |
| Swirl | 1.5 |
| Intake Temperature (C) | 50 |
| Intake Pressure (kPa) | 130 |
| EGR (%) | 0 |

## Fuels

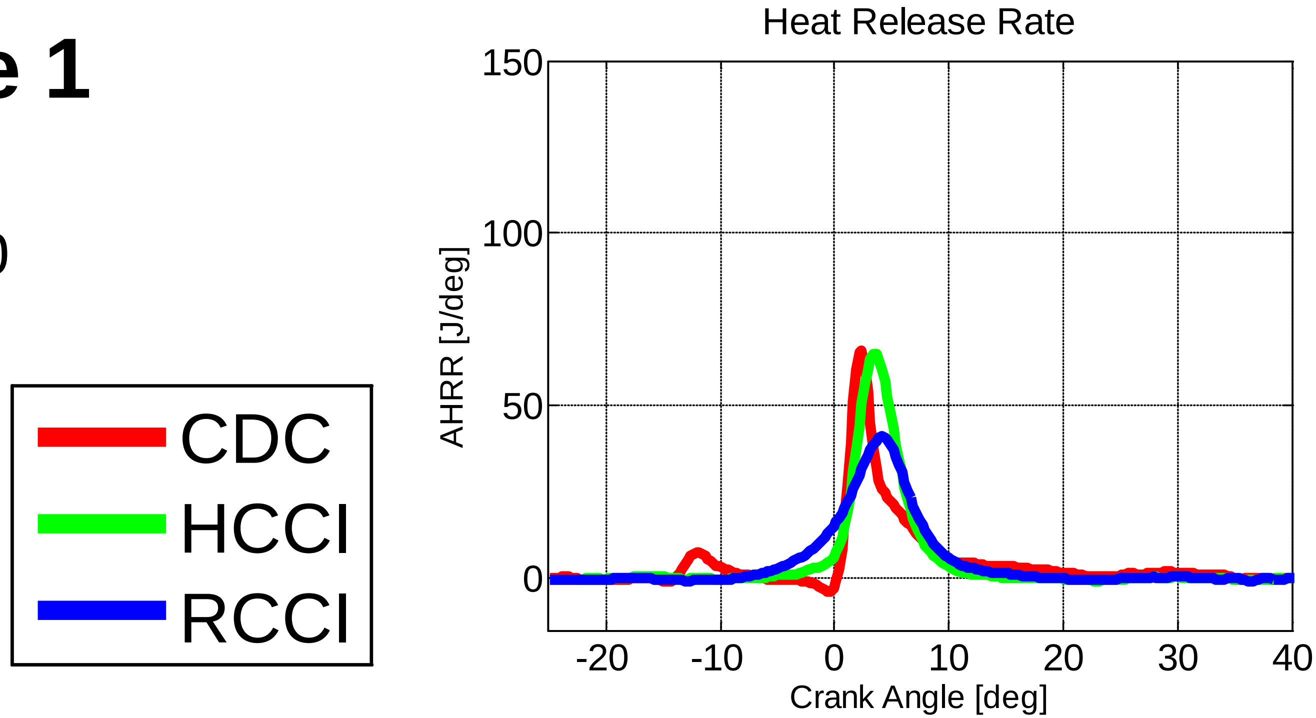
| Regime | Fuel |
|---|---|
| HCCI | 91PON Gasoline / n-heptane |
| RCCI | F76 / 91PON Gasoline |
| CDC | F76 |

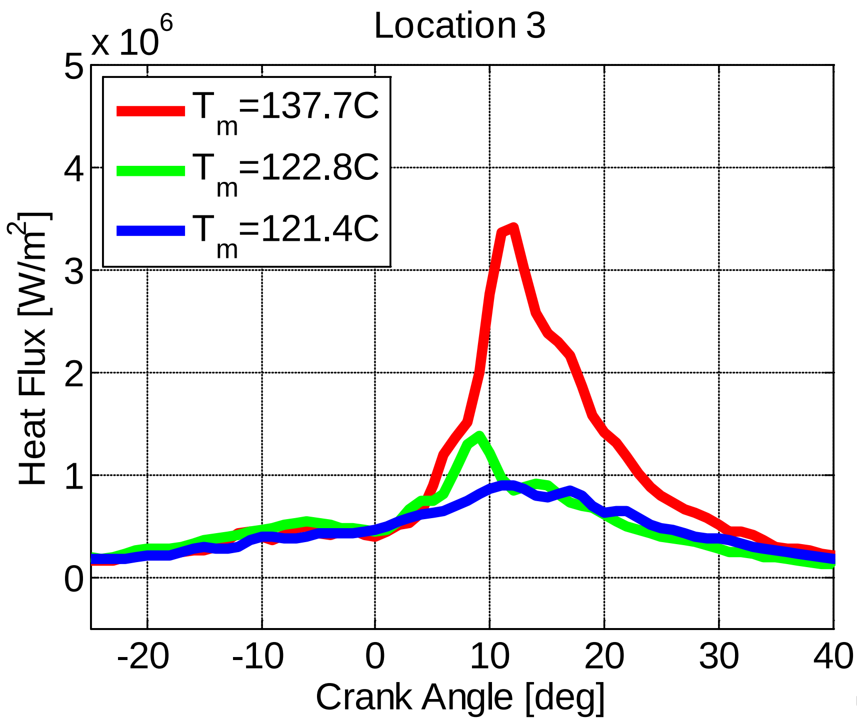
# Mode 1

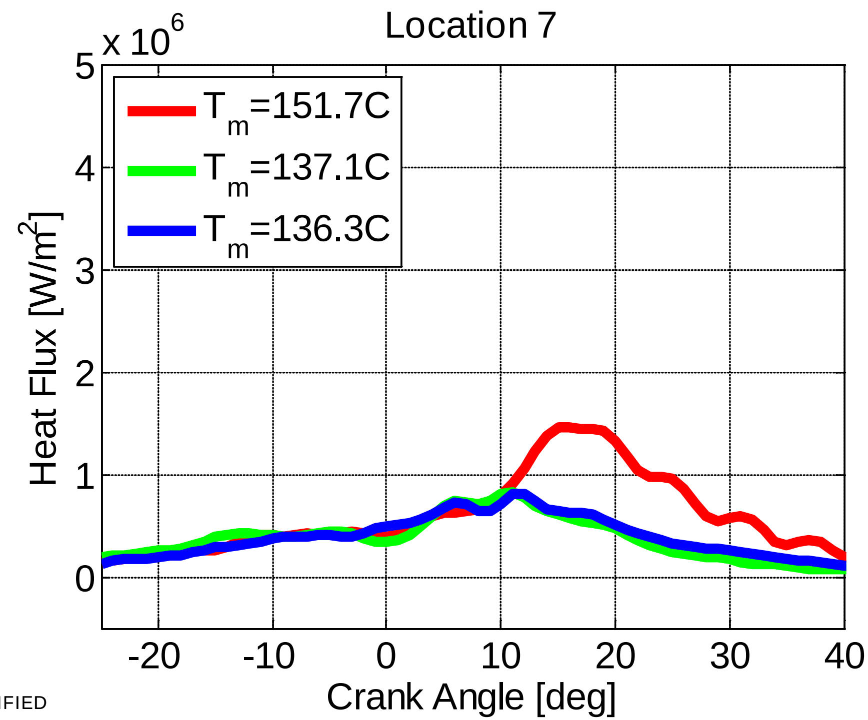
4.2 bar IMEPg

4 degATDC CA50

1490 RPM



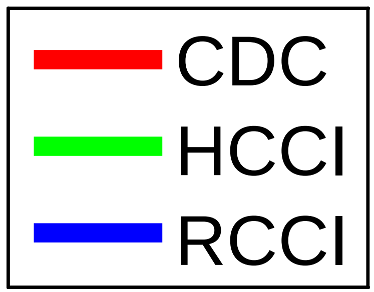



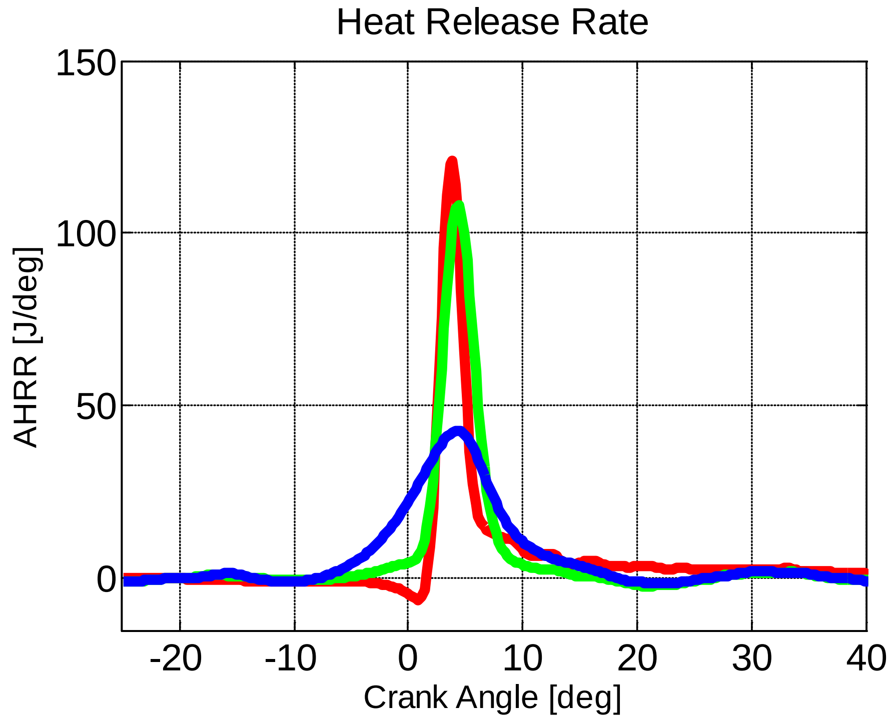
# Mode 2

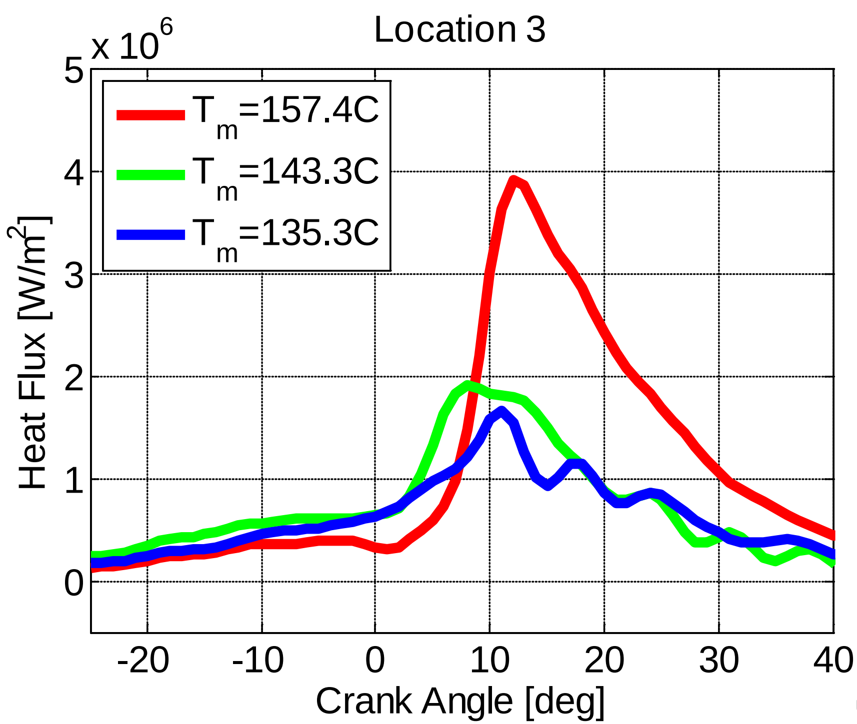
5.7 bar IMEPg

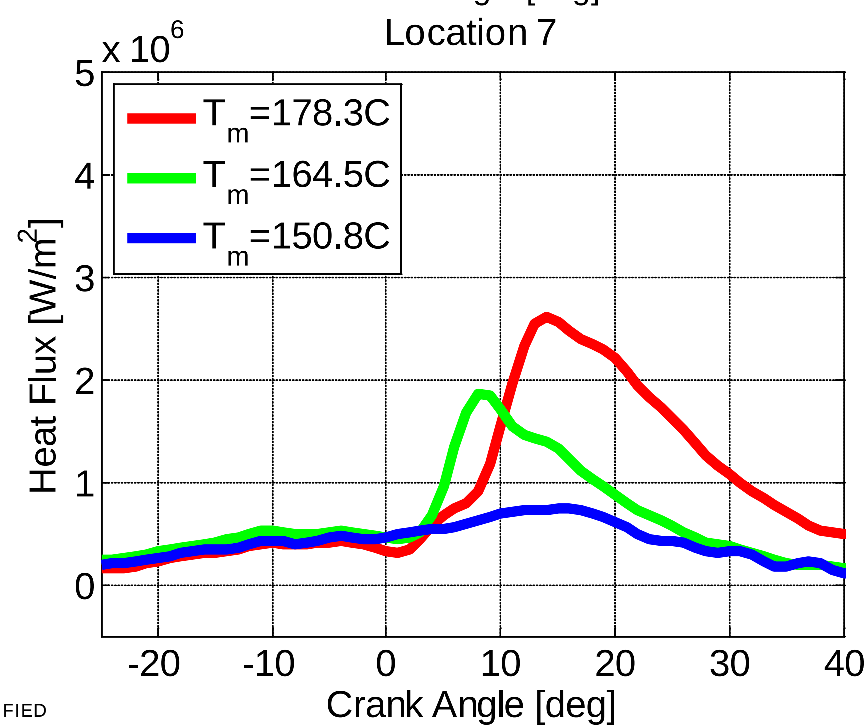
5 degATDC CA50

1900 RPM



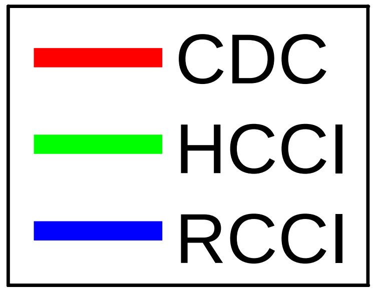



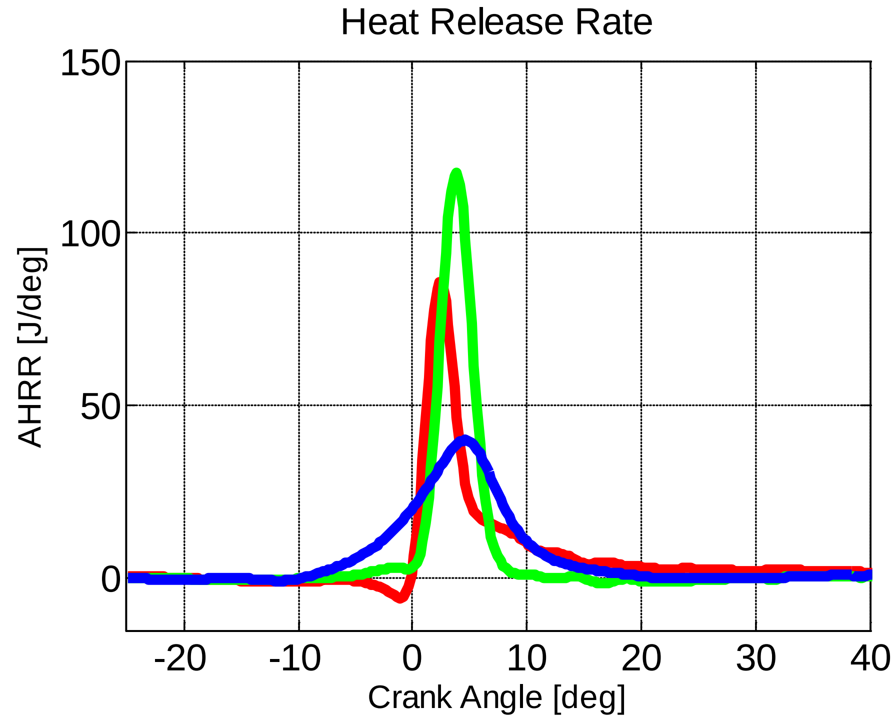
# Mode 3

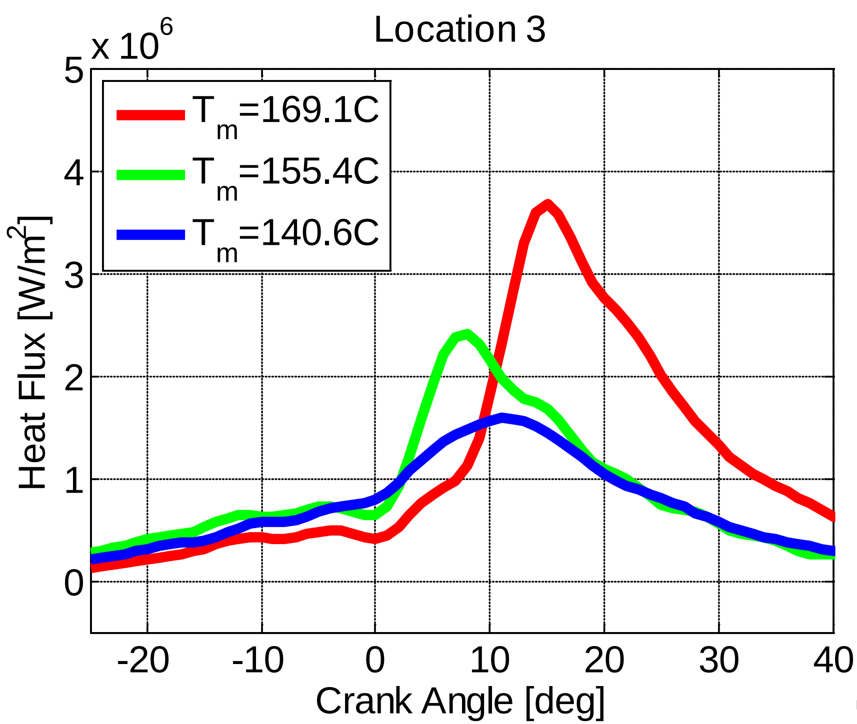
5.7 bar IMEPg

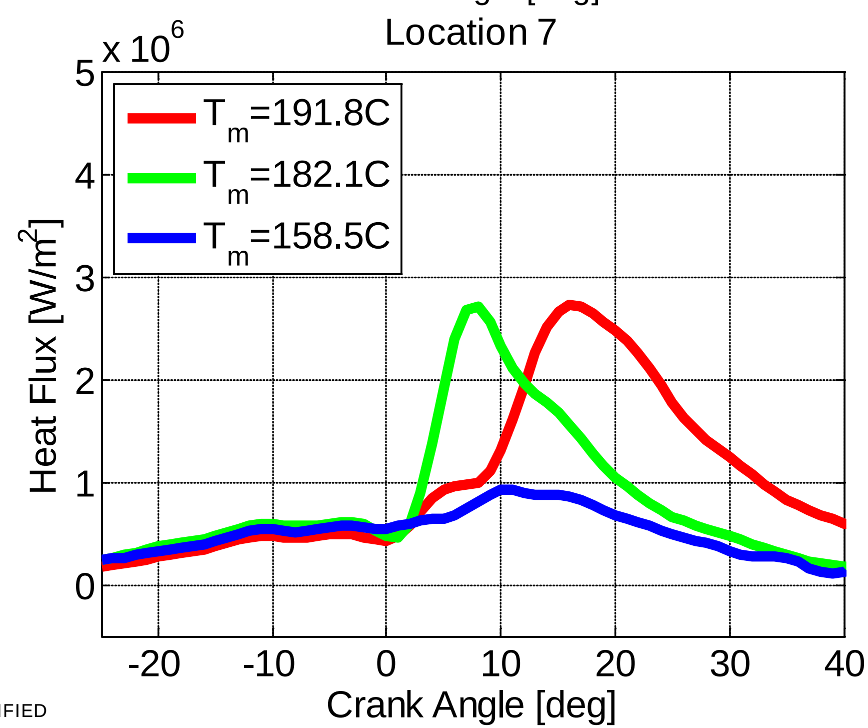
5 degATDC CA50

2300 RPM



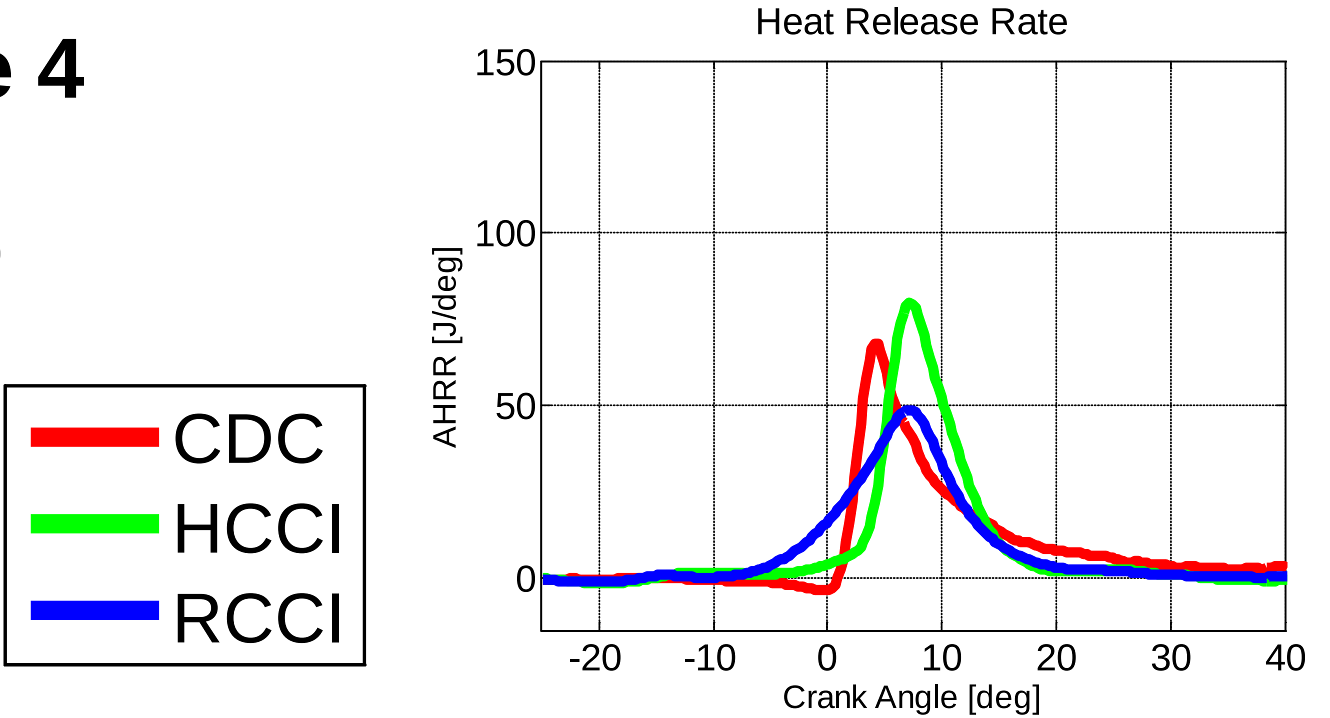



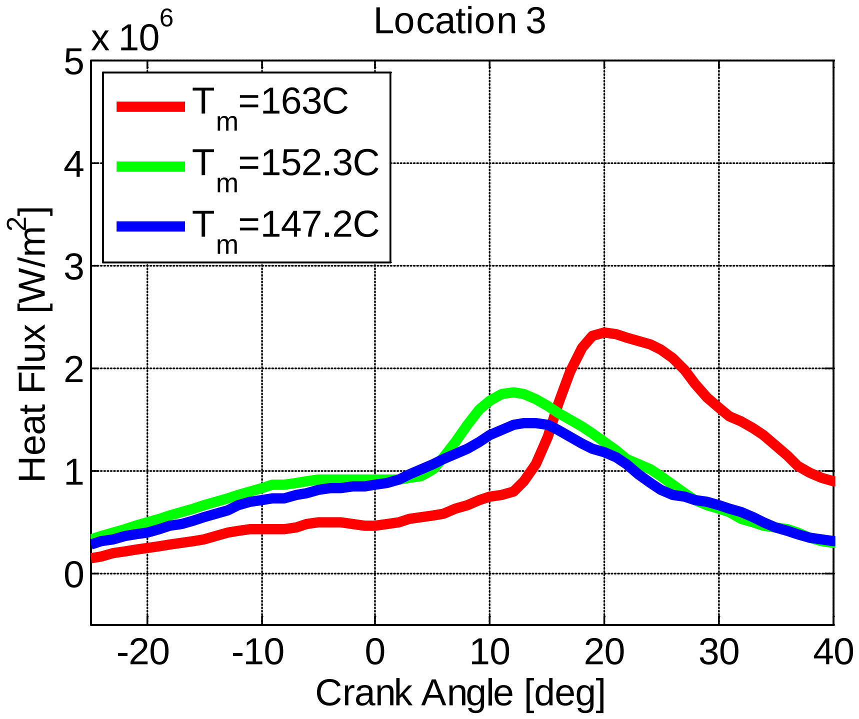



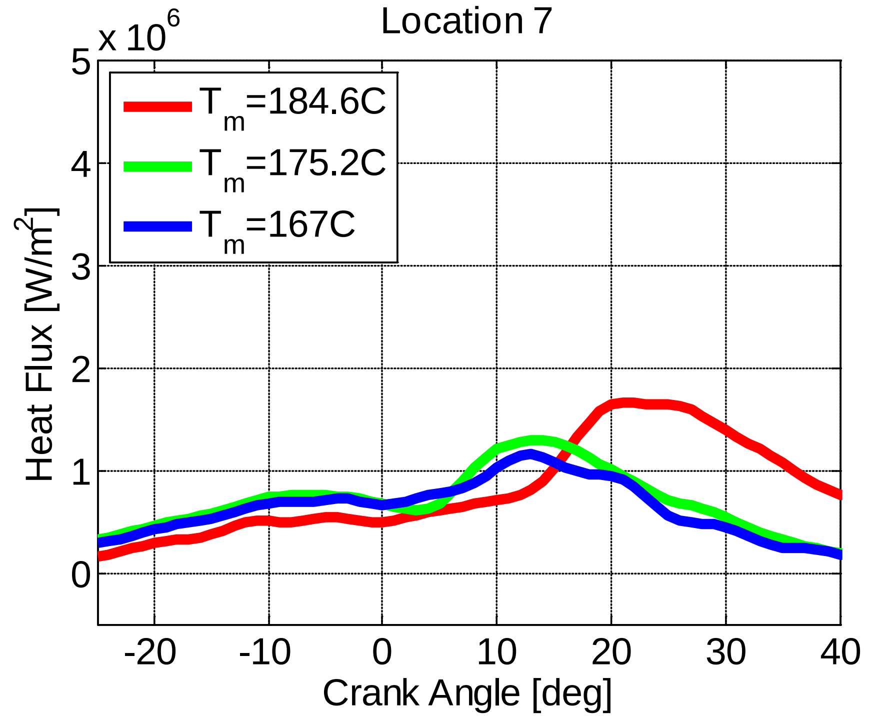



# Mode 4

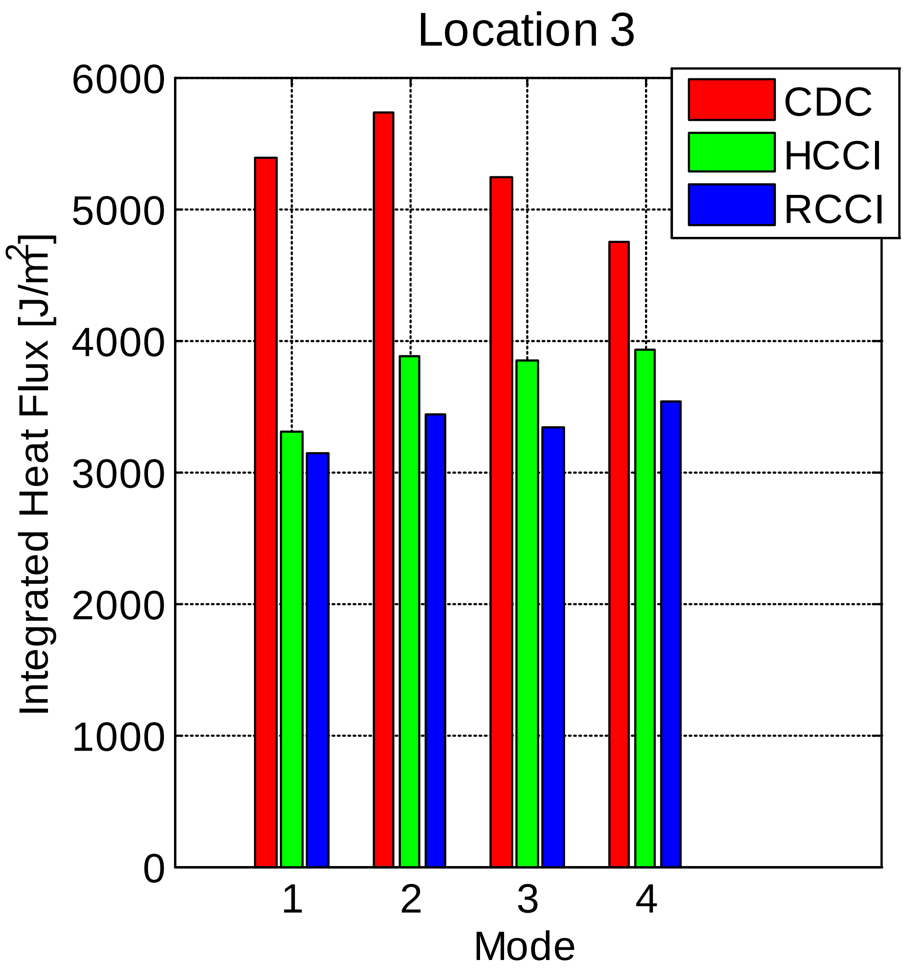
8 bar IMEPg
8 degATDC CA50
2300 RPM

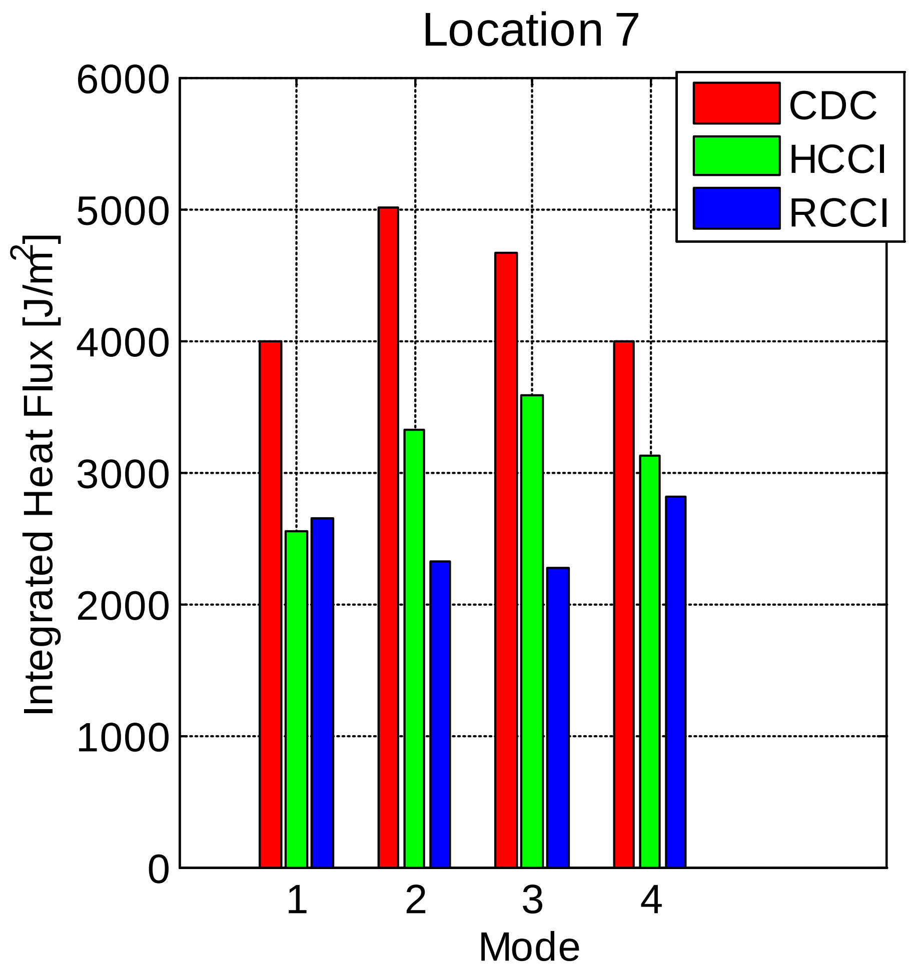


# Closed-cycle Integrated Heat Flux

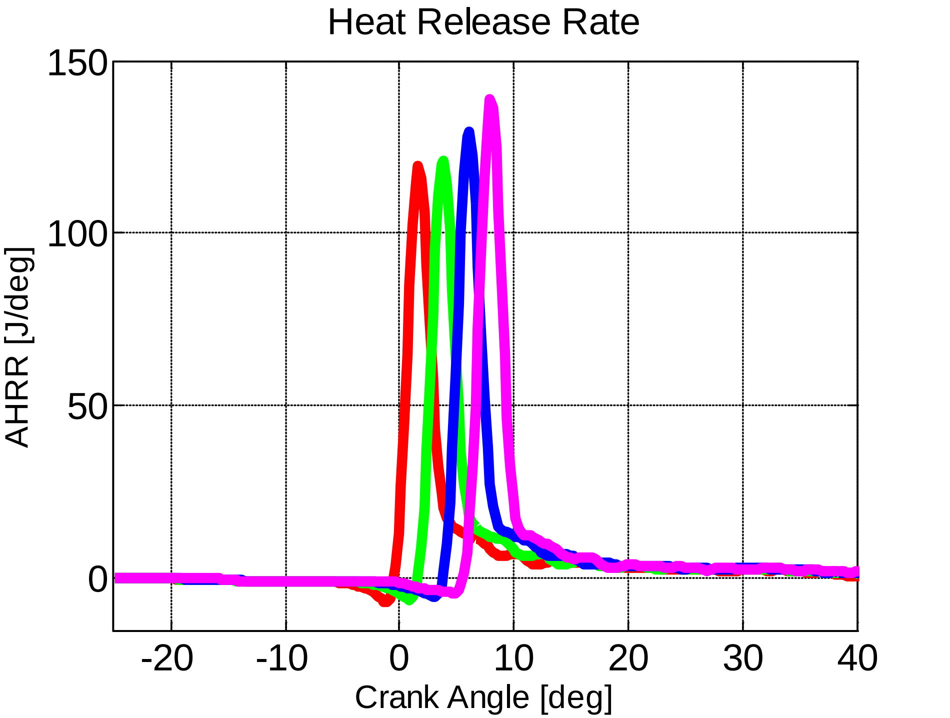


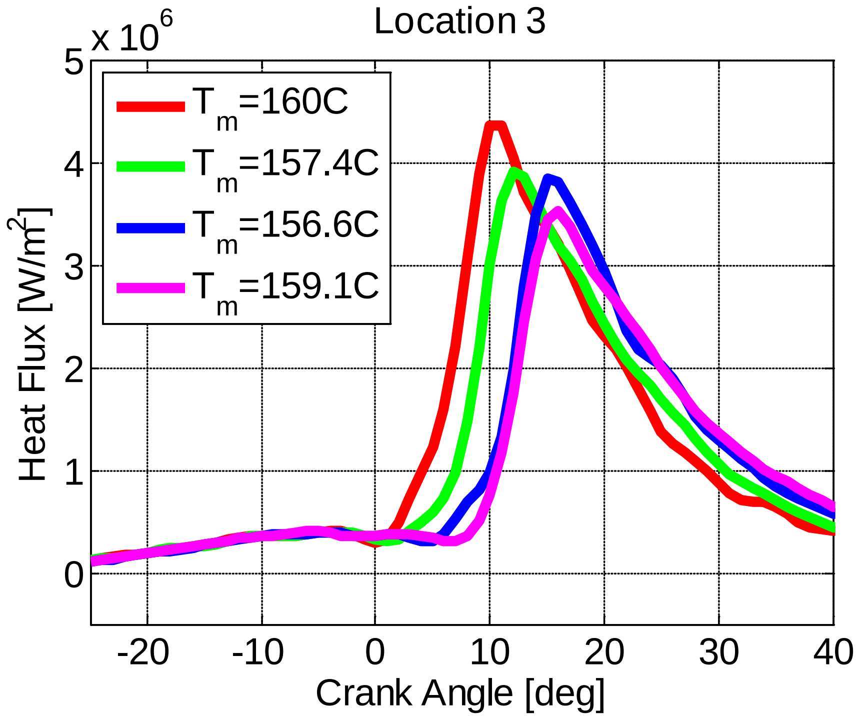



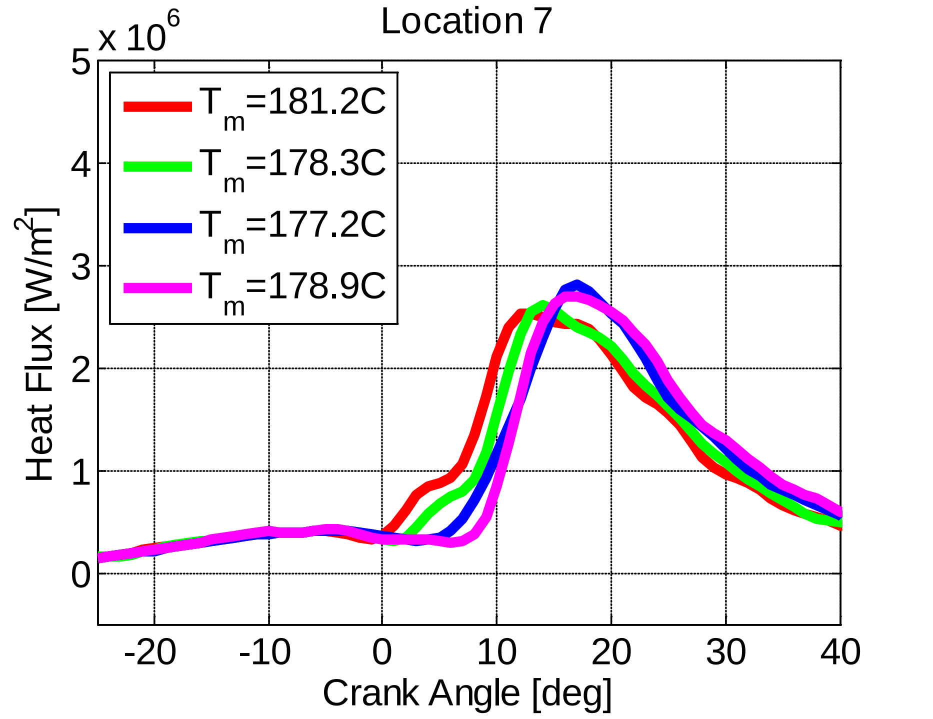
# CDC CA50 Sweep

3degATDC
5degATDC
7degATDC
9degATDC

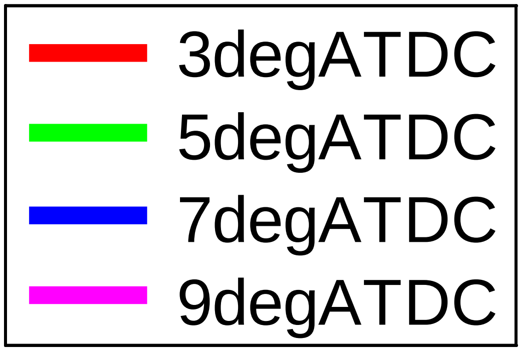
Fixed 5.7bar IMEPg



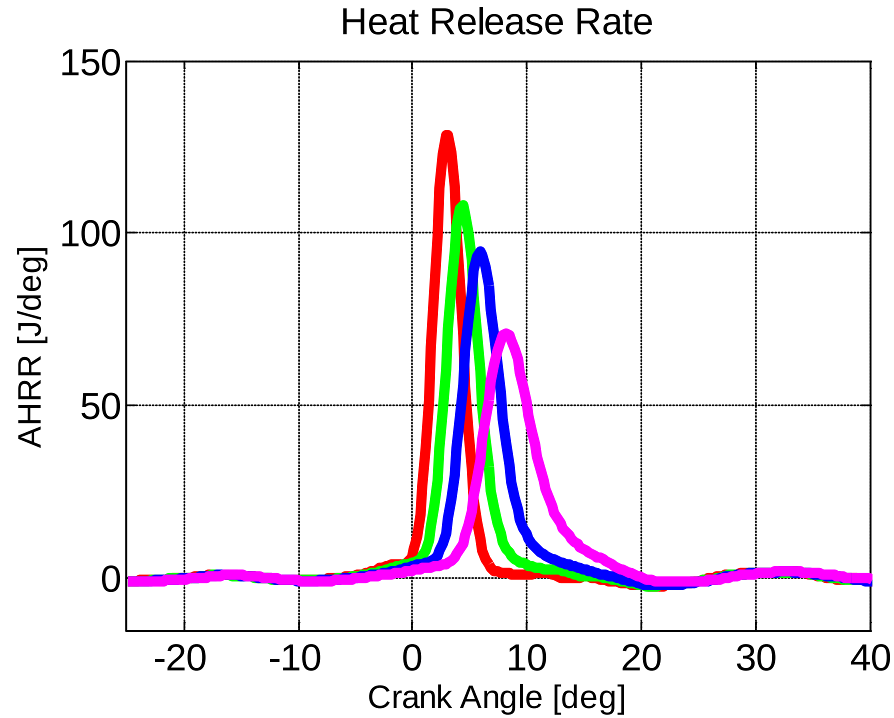



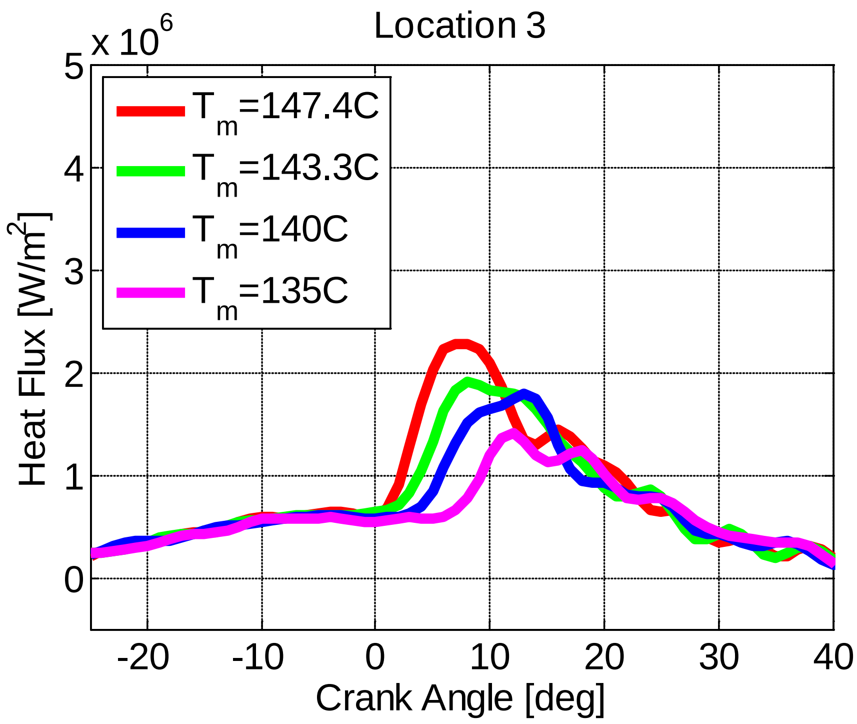



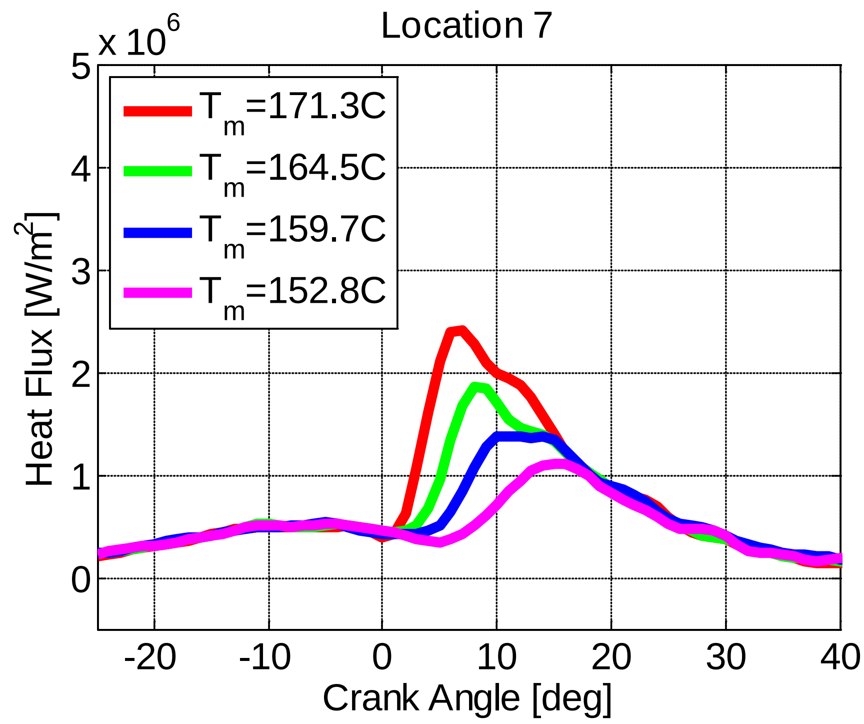
# HCCI CA50 Sweep



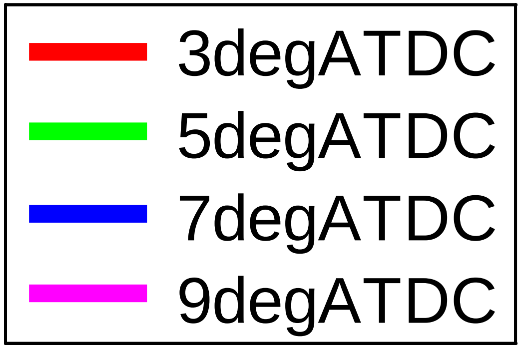

Fixed 5.7bar IMEPg



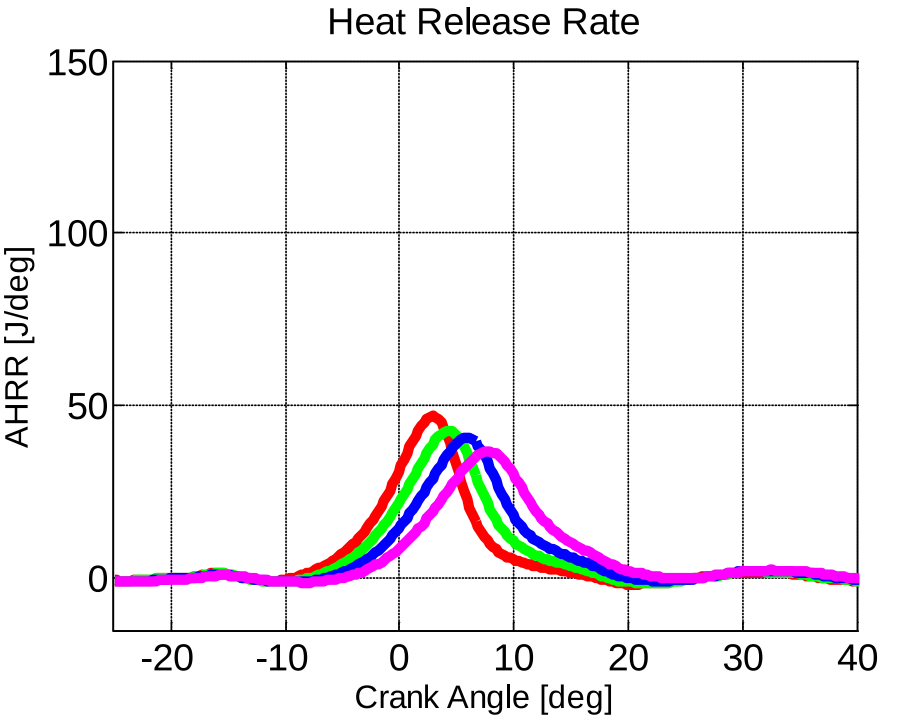



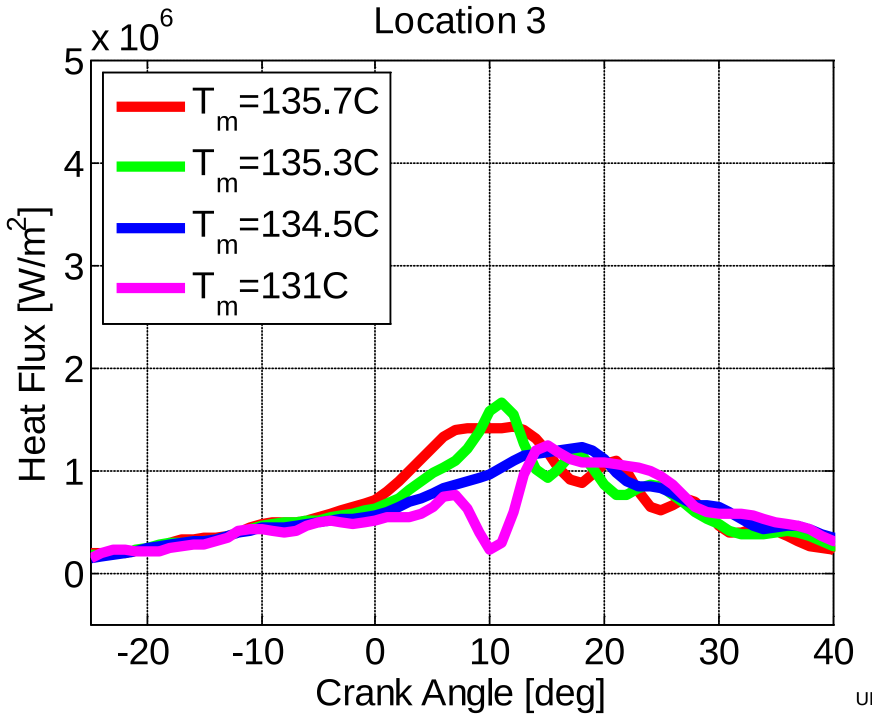



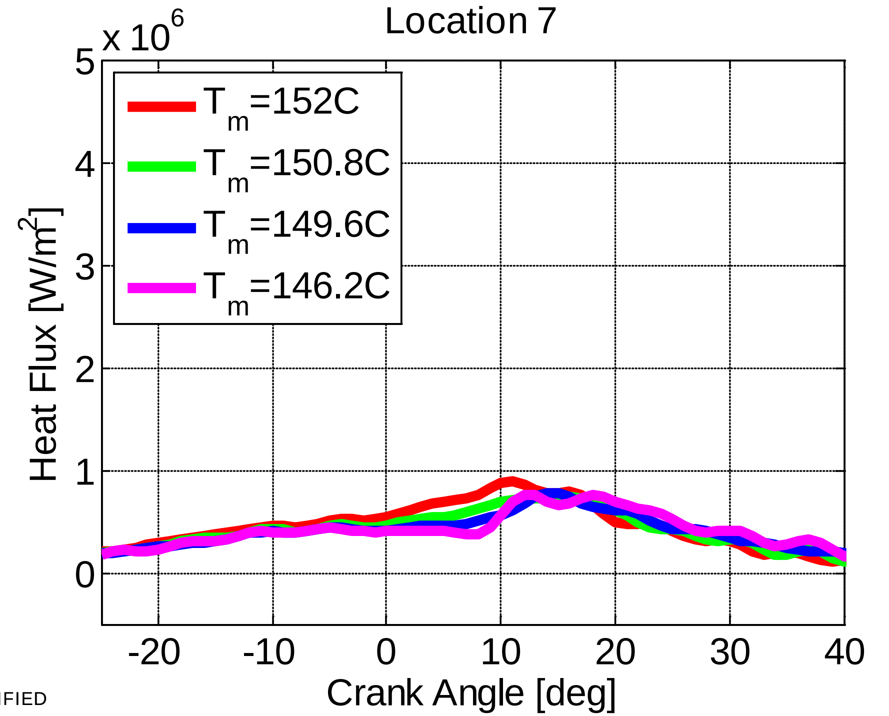
# RCCI CA50 Sweep



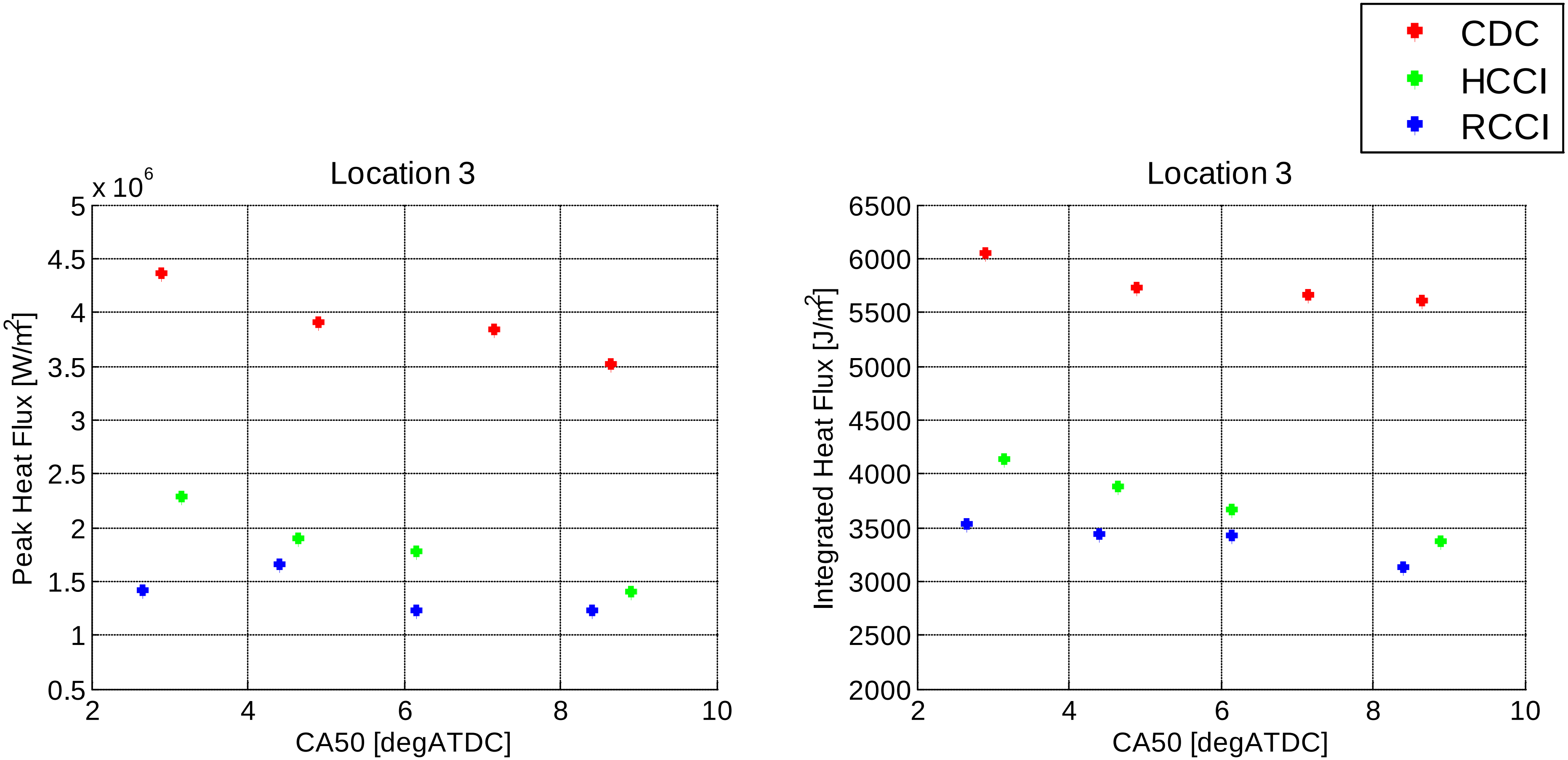

Fixed 5.7bar IMEPg



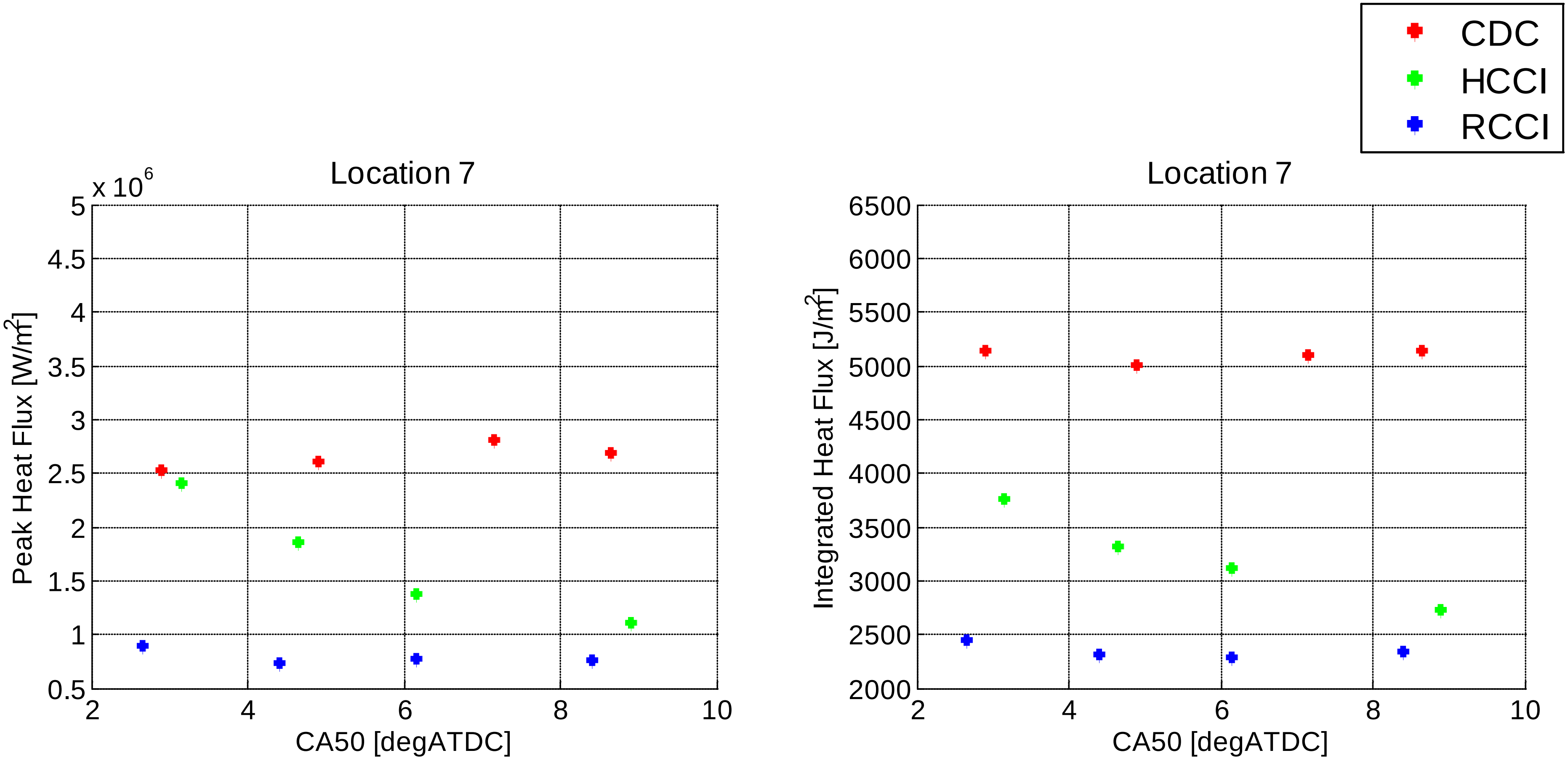



# CA50 Sweep Summary



# CA50 Sweep Summary

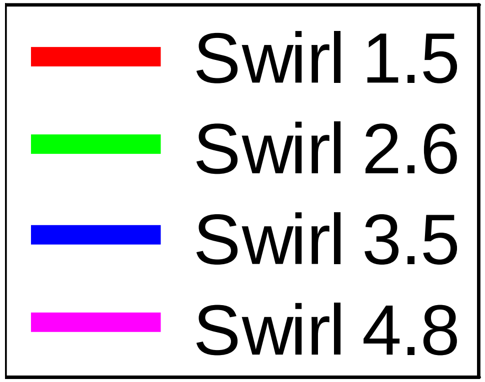


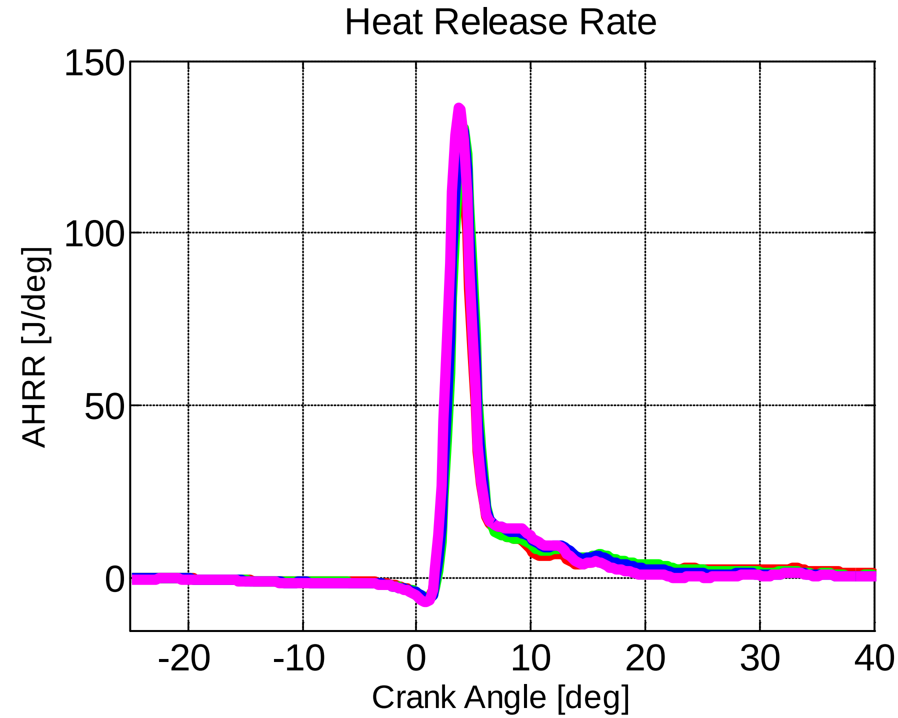


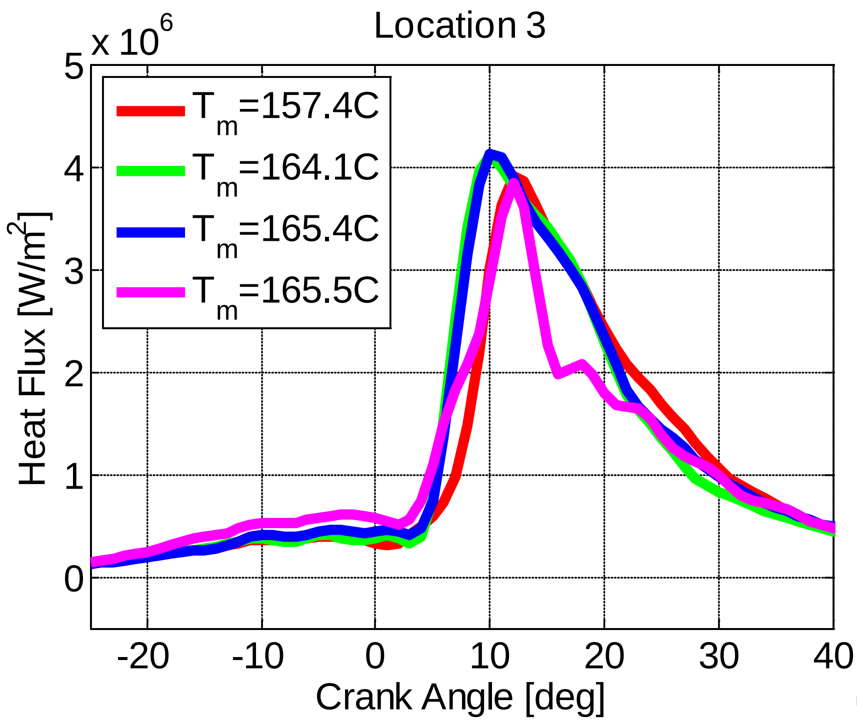
# CDC Swirl Sweep

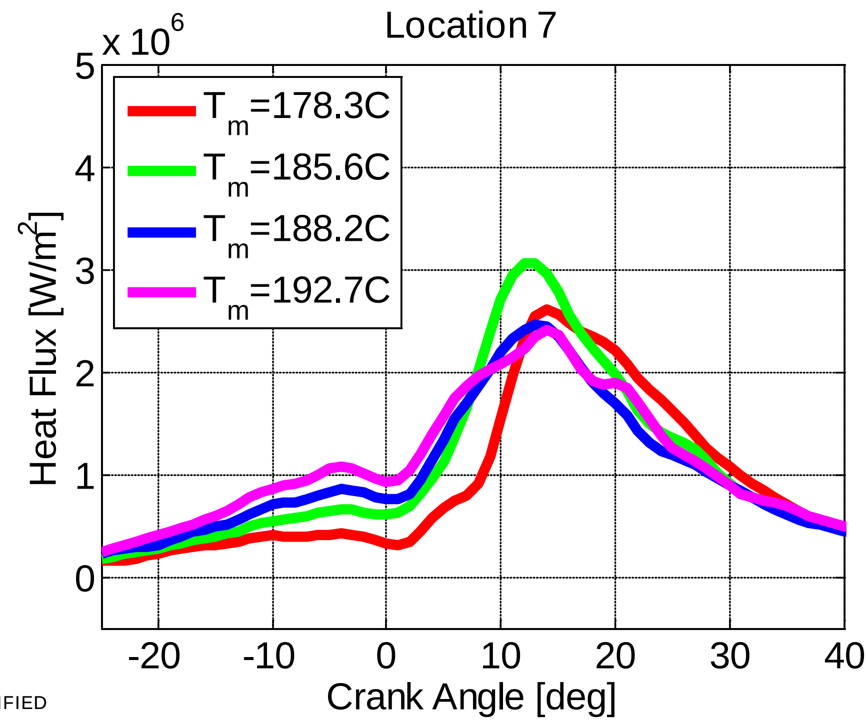
Fixed 5.7 bar IMEPg

Fixed 5 degATDC CA50



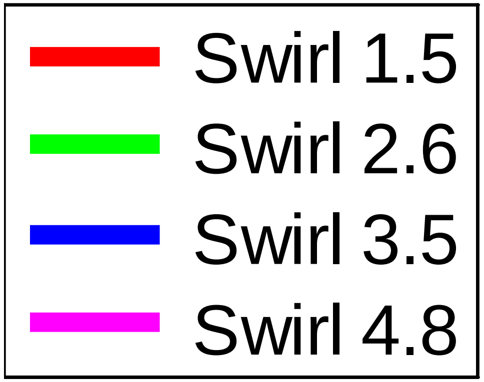



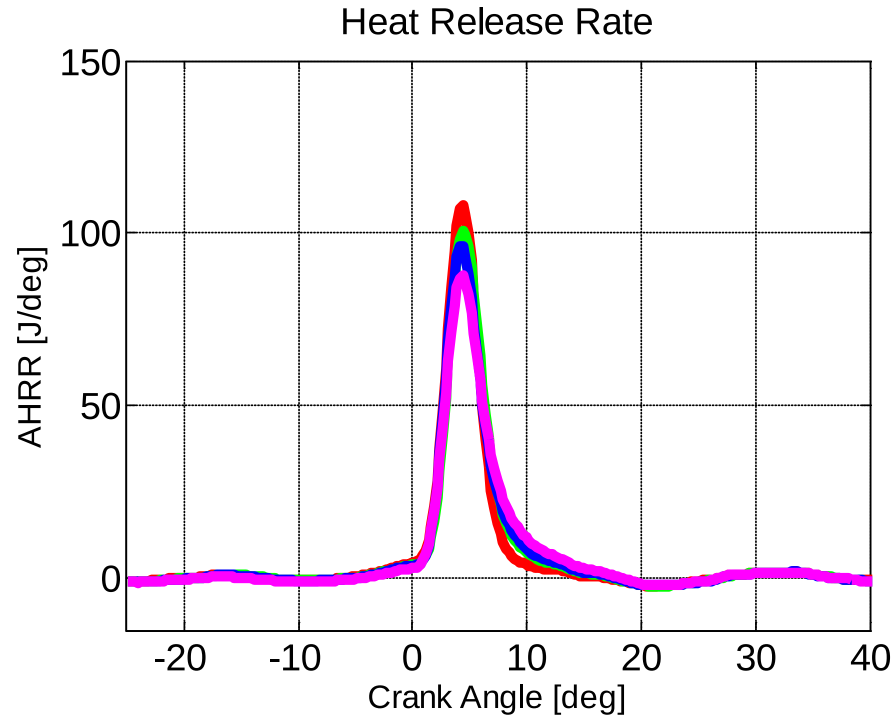



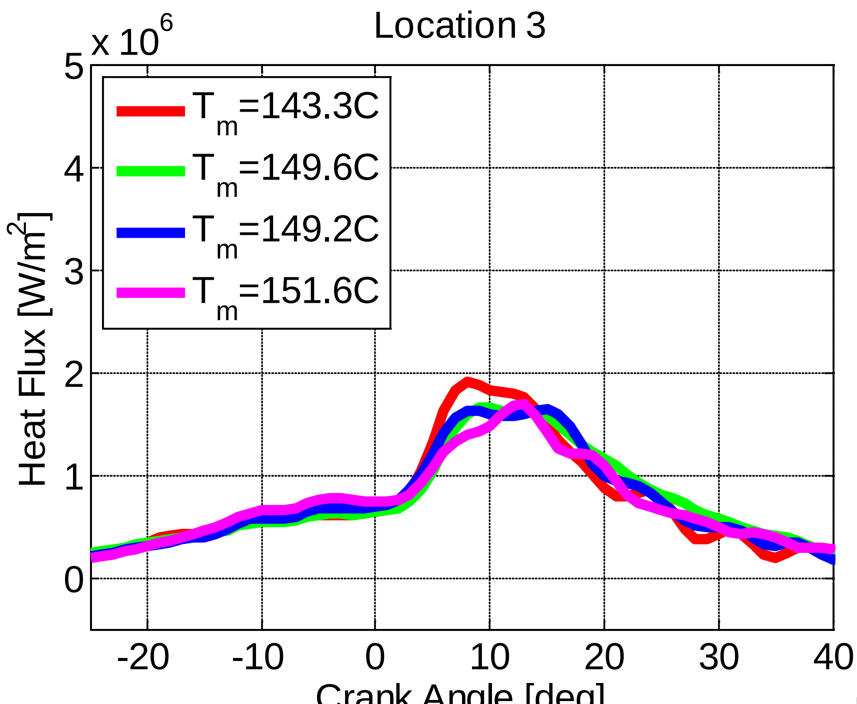
# HCCI Swirl Sweep

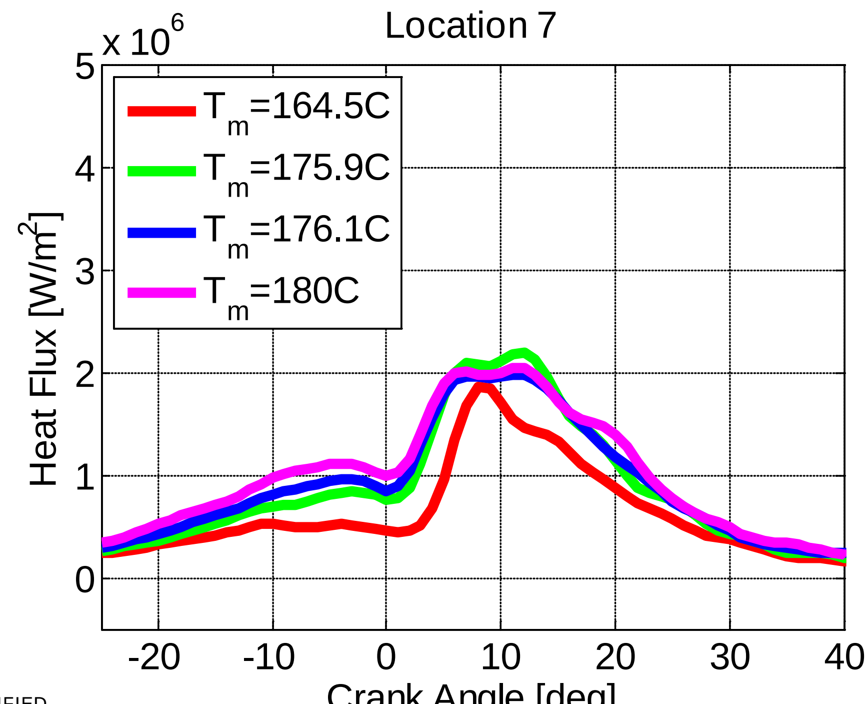
Fixed 5.7 bar IMEPg

Fixed 5 degATDC CA50



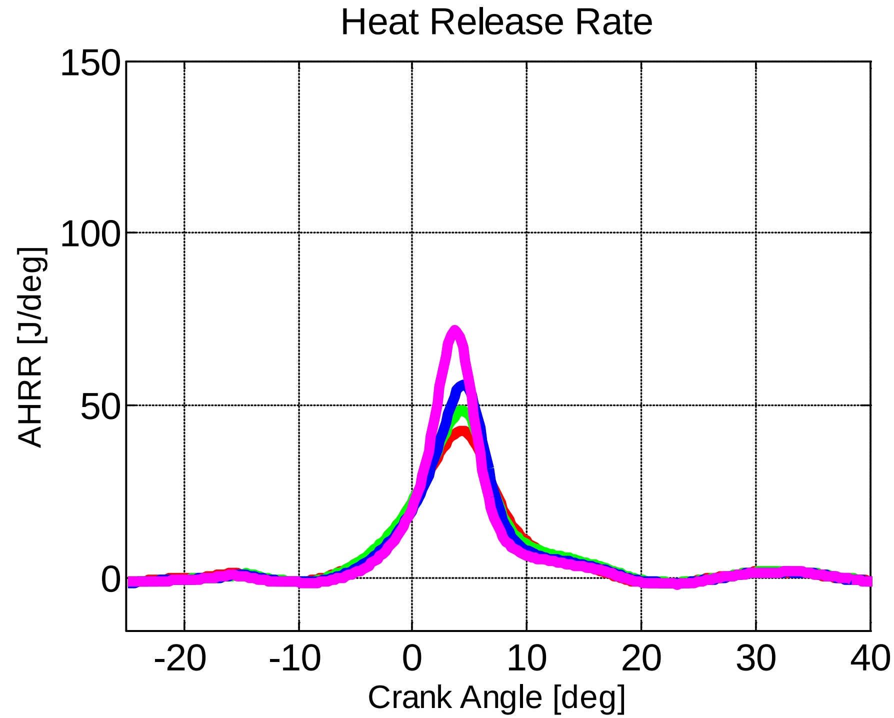



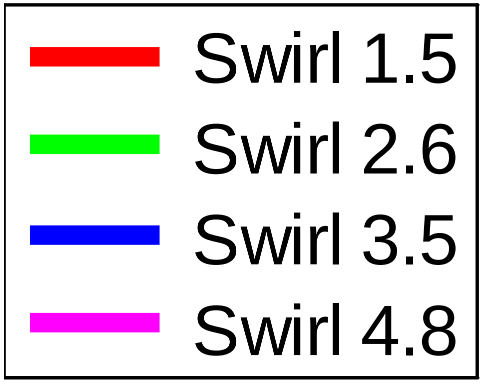



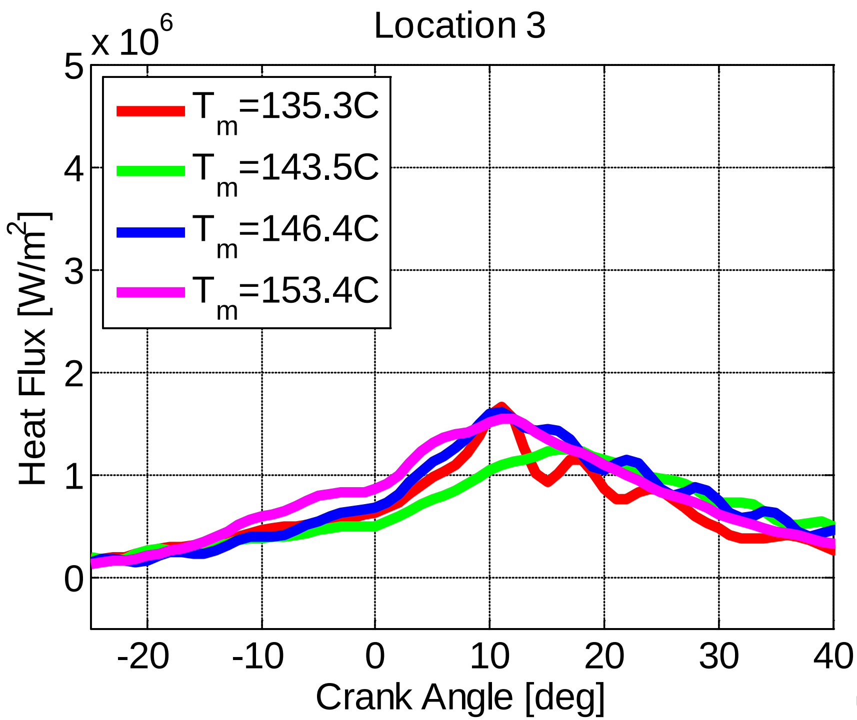
# RCCI Swirl Sweep

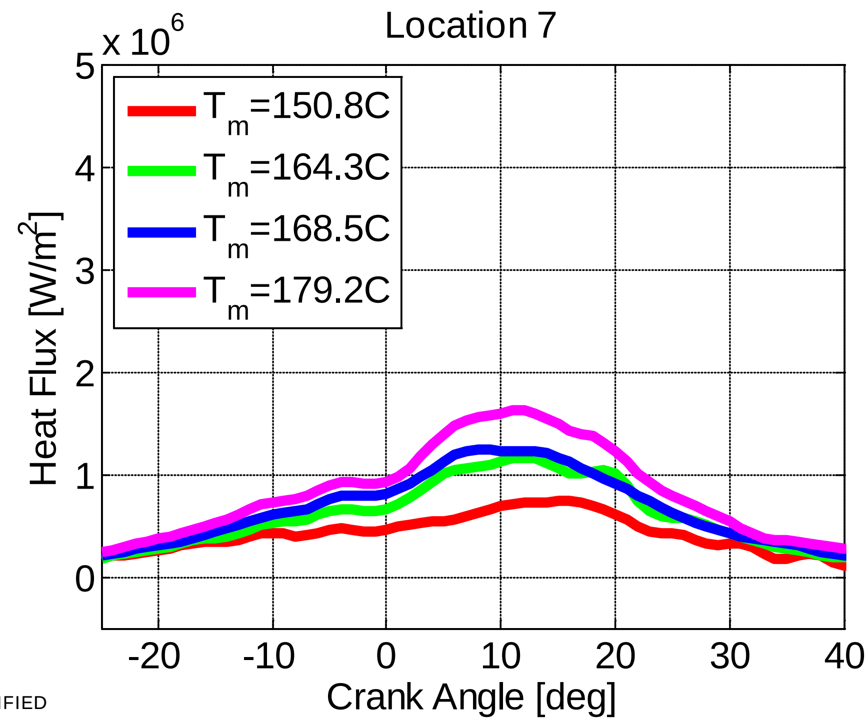
Fixed 5.7 bar IMEPg

Fixed 5 degATDC CA50



# Conclusions

- RCCI and HCCI had a lower peak and closed-cycle integrated heat flux than CDC for all cases. The LTC strategies have lower in-cylinder temperatures than CDC, which is considered to be the main effect. Locally rich areas in CDC also lead to the formation of soot, which may also impact the heat flux; soot radiation is not expected to be present in LTC.
- HCCI peak heat flux was similar to RCCI except for cases when the combustion duration for HCCI was significantly shorter than for RCCI, causing a violent combustion event with a high PPRR. The high PPRR events may have an effect on the piston boundary layer, causing HCCI heat flux to more closely resemble CDC.
- An increase in swirl caused an increase in peak and closed-cycle integrated heat flux for RCCI and HCCI, but the trend was not as apparent for CDC. CDC is a stochastic process with directional spray plumes. Swirl may redirect the location of the plumes onto or away from the thermocouples, affecting the measured heat flux at each location.
- As CA50 is advanced the peak and closed-cycle integrated heat flux increases for HCCI. RCCI and HCCI have similar peak heat flux for retarded CA50 but as CA50 is advanced the peak heat flux increases for HCCI. The peak HCCI heat flux measured in the squish region is more strongly affected and begins to more closely resemble CDC.

# Thank You!

# Questions?

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As the authors are not Government employees, this document was only reviewed for export controls, and improper Army association or emblem usage considerations. All other legal considerations are the responsibility of the author and his/her/their employers.

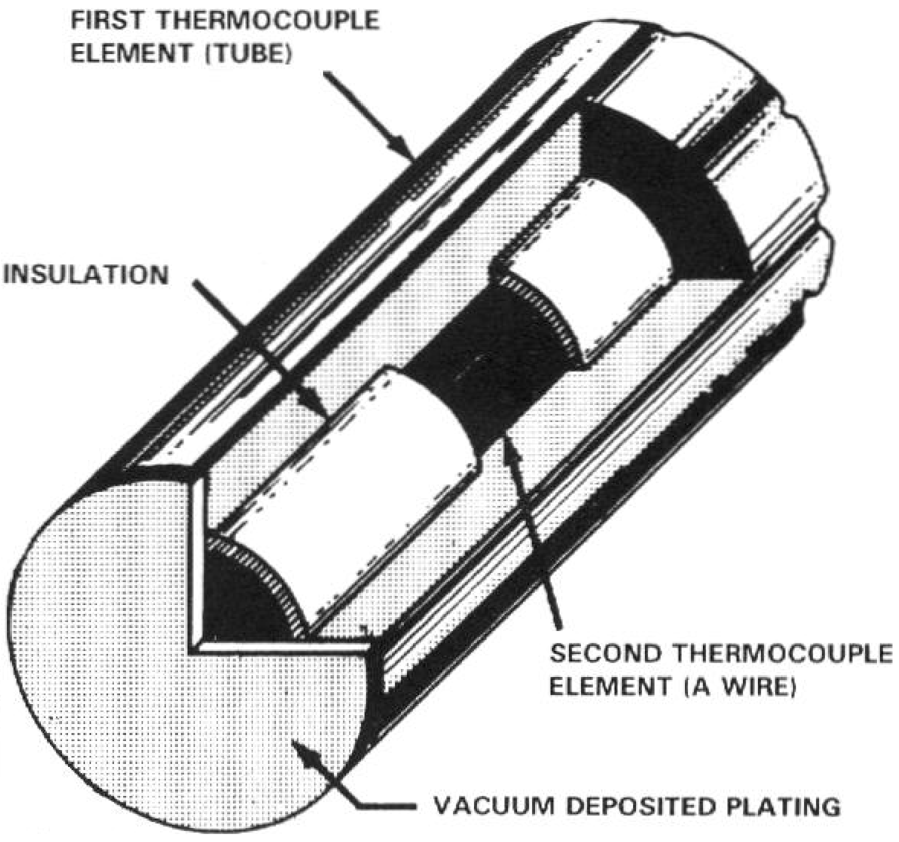
# References


- Rosner, Bernard (May 1983), Percentage Points for a Generalized ESD Many-Outlier Procedure, *Technometrics*, 25(2), pp. 165-172.
- IR Telemetrics, http://www.irtelemetrics.com, last checked 4/19/2012
- MEDTHERM CORP, Coaxial Surface Thermocouple Probes, Bulletin 500, 2006.

# Backup Slides

# Coaxial Thermocouple

- J-type thermocouple
  - Outer tube: Iron
  - Wire: Constantan
  - Temperature Range: -270-400°C
- Plated with Chromium
  - ~1μs time constant
- Cold-weld sliver
  - ~10μs time constant
  - Contour fit
- Electrical insulation wrapped around outer most element (tri-axial)
- Thermocouples manufactured and installed by MEDTHERM

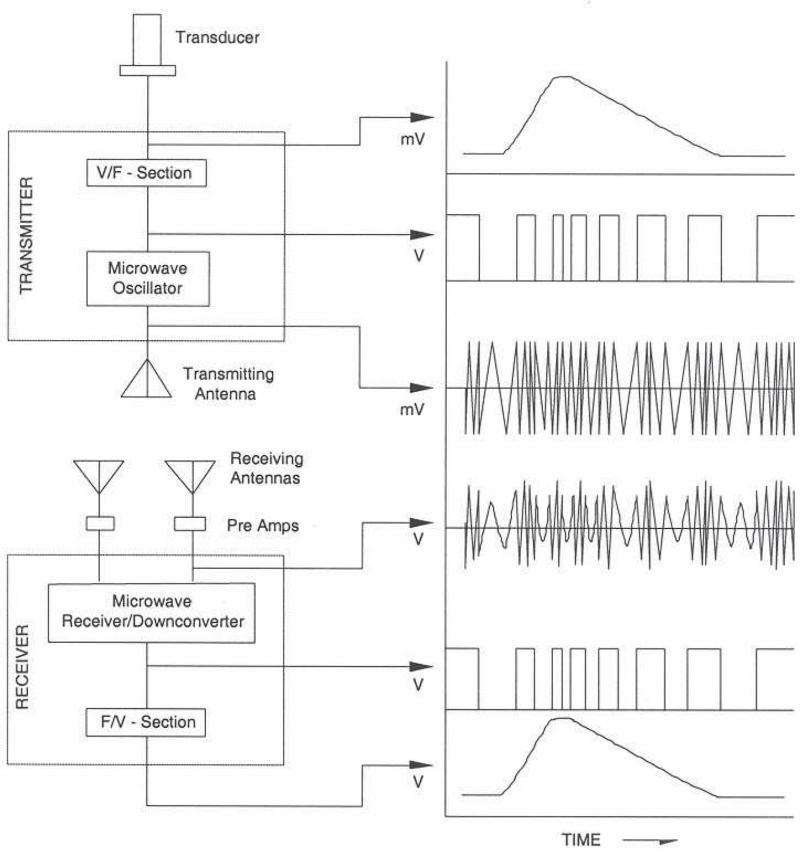



(MEDTHERM CORP, Bulletin 500)

# Telemetry System



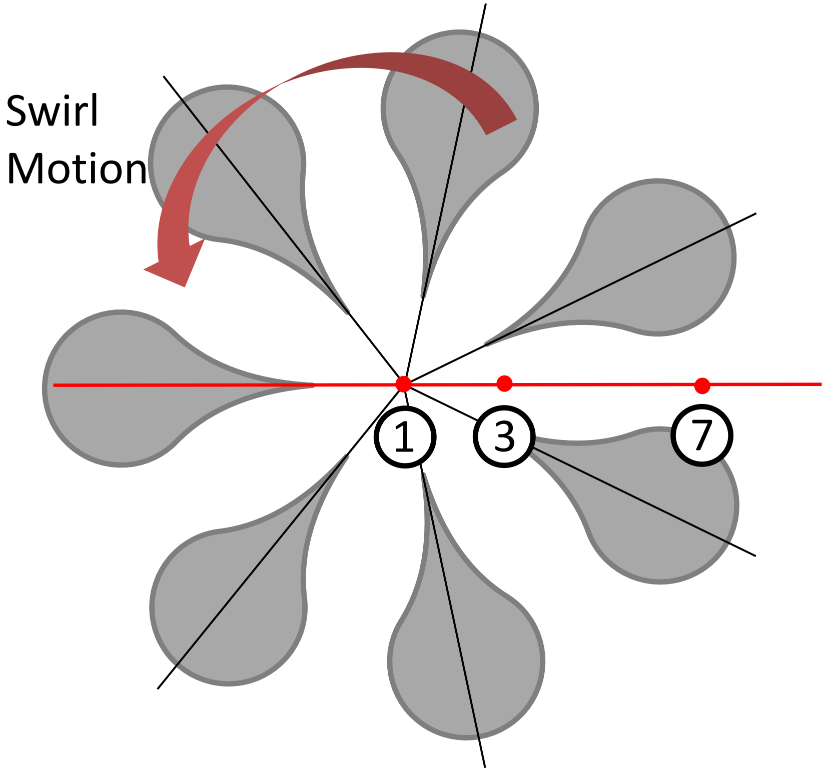
- 10 kHz advertised bandwidth
- 8 channels (7 thermocouples +1 marker)
- Multiplex configured at 0.50 seconds per channel
- Data recorded for 120 seconds
- Higher engine speeds yield more engine cycles




(www.irtelemetrics.com)

# Spray Location





# Injection Timings



| | | CDC | | | RCCI | | |
|---|---|---|---|---|---|---|---|
| | | Injection Timing | Injection Duration | Injection Pressure | Injection Timing | Injection Duration | Injection Pressure |
| Combustion Phasing Effect | 3degATDC | -10 | 0.531 | 1000 | -56 / -36 | 0.296 / 0.261 | 500 |
| | 5degATDC | -8 | 0.53 | 1000 | -59 / -39 | 0.82 / 0.256 | 500 |
| | 7degATDC | -6 | 0.532 | 1000 | -63 / -43 | 0.565 / 0.252 | 500 |
| | 9degATDC | -4.5 | 0.534 | 1000 | -65 / -45 | 0.255 / 0.250 | 500 |
| | | | | | | | |
| Swirl Effect | 1.5 Swirl | -8 | 0.53 | 1000 | -59 / -39 | 0.281 / 0.256 | 500 |
| | 2.6 Swirl | -8 | 0.531 | 1000 | -58 / -38 | 0.270 / 0.266 | 500 |
| | 3.5 Swirl | -8 | 0.53 | 1000 | -59 / -39 | 0.265 / 0.266 | 500 |
| | 4.8 Swirl | -8 | 0.53 | 1000 | -59 / -39 | 0.265 / 0.266 | 500 |
| | | | | | | | |
| Combustion Strategy Effect | Mode 1 | -26 / -6 | .0.25 / 0.453 | 1000 | -44 | 0.286 | 500 |
| | Mode 2 | -8 | 0.53 | 1000 | -59 / -39 | 0.810 /0.256 | 500 |
| | Mode 3 | -11 | 0.531 | 1000 | -57 / -37 | 0.286 / 0.261 | 500 |
| | Mode 4 | -10 | 0.607 | 1000 | -60 / -40 | 0.278 / 0.250 | 500 |

*Note if two values are listed a dual injection stagey was used